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CHARGE YIELD AND DOSE EFFECTS IN MOS CAPACITORS AT 80 K.(U)

MAY 77 H E BOESCH, J M MCGARRITY

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The response of metal-oxide semiconductor capacitors to short-pulse high-energy electron irradiation was measured at 80 K. It was confirmed that radiation-generated holes are almost totally retained in the SiO_2 layer regardless of oxide processing; this retention was exploited to determine carrier yield as a function of applied electric field. Evidence was found that the holes

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undergo an initial displacement under an applied field immediately following carrier generation (9.5 nm at 10^6 V/cm). Samples were subjected to pulsed irradiation at 80 K to accumulated doses above 10^6 rads(SiO_2) and mechanisms which limit hole buildup above 5×10^4 rads(SiO_2) were explored. Electron-hole recombination in a low field region of the SiO_2 was identified as an important process and was modeled. Other mechanisms discussed include electron injection, field- and temperature-activated hole transport, applied field collapse, and dielectric breakdown.

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1. INTRODUCTION

Metal-oxide semiconductor (MOS) devices, such as charge-coupled devices (CCD's) and MOSFET's (MOS field-effect transistors), are being investigated for use in imaging, signal processing, and detector preamplifier applications in which the detector and its immediately associated electronics are operated at low temperatures ($\leq$80 K). Recent experiments on MOS capacitors and devices at ~80 K have established that, when hole-electron pairs are generated in the SiO_2 insulating layer by ionizing radiation, the electrons are rapidly swept out of the oxide while the holes remain essentially immobile ("frozen in") at or near their point of creation.[1,2,3] As a result, most of the holes generated by the radiation remain in place in the oxide layer for significant times and cause relatively large flatband- or threshold-voltage shifts per unit dose in MOS structures. (A flatband voltage shift of ~-1 V is expected for a 10-krad(SiO_2) dose in a 100-nm oxide.) These shifts threaten device operation at doses well below 100 krads. In contrast to the highly process-dependent "permanent" trapping of a small fraction (typically 1 to 10 percent) of the radiation-generated holes observed at room temperature in "hard" MOS oxides, the retention of the holes in SiO_2 at ~80 K is largely process independent[2] and results from a strongly temperature-dependent hole-transport mechanism.[1,3,4] Since the yield of electron-hole pairs generated in an MOS oxide per unit radiation dose is believed[5] to be an intrinsic property of amorphous SiO_2, this yield also should be process independent. Therefore, if MOSFET's, MOS integrated circuits (IC's), or charge-coupled devices with pure SiO_2 gate-insulator layers are operated and irradiated at low temperatures, they will suffer relatively large oxide-charge buildups whether or not they have been hardened to charge trapping at room temperature.

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[1] *H. E. Boesch, Jr., F. B. McLean, J. M. McGarrity, and G. A. Ausman, Jr., IEEE Trans. Nucl. Sci. NS-22, 2163 (1975).*

[2] *H. H. Sander and B. L. Gregory, IEEE Trans. Nucl. Sci. NS-22, 2157 (1975).*

[3] *R. C. Hughes, E. P. Eer Nisse, and H. J. Stein, IEEE Trans. Nucl. Sci. NS-22, 2227 (1975).*

[4] *F. B. McLean, H. E. Boesch, Jr., and J. M. McGarrity, Hole Transport and Recovery Characteristics of MOS Gate Insulators, IEEE Nuclear and Space Radiation Effects Conference (July 1976).*

[5] *G. A. Ausman, Jr., and F. B. McLean, Appl. Phys. Lett. 26, 173 (1975).*

The present report discusses two related investigations of radiation-induced charge buildup in SiO_2 at ~80 K. In the first study, the retention of holes at low temperature was exploited to provide a direct measure of hole-electron pair yield per unit radiation dose at low temperature as a function of electric field for high-energy ionizing radiation. In the second study, the response of MOS capacitors to short-pulse high-dose irradiation at ~80 K was investigated, and mechanisms which impose limits on the oxide-charge buildup were examined.

2. SAMPLES AND EXPERIMENTAL TECHNIQUES

Dry-grown oxide samples were provided by Hughes Aircraft Corporation (HAC), Northrop Research and Technology Center (NRTC), and a proprietary source supported by the Defense Nuclear Agency (DNA). HAC also supplied a wet-oxide sample representative of the process under development in their hardened complementary-MOS/silicon-on-sapphire program. The dry oxides were thermally grown at 1000°C and the wet oxide was pyrogenically grown at 950°C, usually on n-type Si (see table I). Aluminum gate electrodes were deposited, and the resulting MOS capacitors were bonded to headers without caps.

TABLE I. MOS CAPACITOR SiO_2 CHARACTERISTICS

Identifier	Gate deposition	Post anneal	Oxide thickness (nm)
DNA No. 1	filament	A, 15 m, 800°C	72.5
DNA No. 2	filament	None	65.5
HAC dry n	C crucible	None	87.5
HAC dry p	C crucible	None	87.5
HAC wet n	C crucible	N_2, 20 m, 925°C	96.5
NRTC 850	e-beam	None	85
NRTC 671	e-beam	None	67
NRTC 1538	e-beam	None	154

The experiments were performed with the electron linear accelerator (LINAC) at the Armed Forces Radiobiology Research Institute (AFRRI). The LINAC produced a nominal 12- to 13-MeV 1-A electron beam with a pulse width of 4 μs. Multiple pulses could be delivered to the sample at a rate of 60/s. Sample dose per pulse was controlled by varying the LINAC-to-sample distance. A thin-foil Cu calorimeter was used for pulse-to-pulse electron-beam dosimetry. Teflon:CaF_2 thin-disc thermoluminescent dosimeters were employed for absolute dose measurements. For the charge-yield experiment, the samples were mounted in a liquid-nitrogen-cooled sample holder under vacuum.[6] For the high-dose experiments, the samples were submerged directly in a liquid-nitrogen bath to insure maximum thermal transfer. For both experiments, data were taken only on the first pulse delivered to a sample. A fast high-frequency capacitance-voltage (C-V) measuring apparatus[6,7] recorded the preirradiation C-V characteristics and monitored these characteristics as a function of time either after a single radiation pulse, or, sometimes, at 1 and 12 ms after each individual radiation pulse in a multiple-pulse burst. The MOS capacitance of the sample was monitored by a phase-sensitive detector system operating at 5 MHz. The C-V characteristics were recorded on oscilloscopes by monitoring the capacitance as a 0.1 ms voltage ramp was applied to the capacitor. The fast C-V system was intercalibrated with a Boonton 71A capacitance meter and found capable of accurately reproducing the deep-depletion C-V trace. From the C-V data, the radiation-induced flatband-voltage shift, ΔV_{FB}, was extracted.

3. CHARGE-YIELD MEASUREMENT

3.1 Field Dependence of Hole Yield

The field (bias) dependence of the yield of charge carriers in SiO_2 was measured by Curtis, Srour and Chiu[8] at room temperature by a charge-collection technique and low-energy (~4-keV) electron irradiation. Ausman and McLean[5] demonstrated that these results were consistent with a hole-electron pair-creation energy W_o ~18 eV/pair,

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[5] *G. A. Ausman, Jr., and F. B. McLean, Appl. Phys. Lett. 26, 173 (1975).*

[6] *H. E. Boesch, Jr., Development of Apparatus for Performing Rapid Capacitance-Voltage Measurements on MIS Structures, Harry Diamond Laboratories TM-76-33 (December 1976).*

[7] *F. B. McLean, H. E. Boesch, Jr., P. S. Winokur, J. M. McGarrity, and R. B. Oswald, Jr., IEEE Trans. Nucl. Sci. NS-21, 47 (1974).*

[8] *O. L. Curtis, Jr., J. R. Srour, and K. Y. Chiu, J. Appl. Phys. 45, 4506 (1974).*

which in turn agrees with results of a model for the ionization process based on plasmon creation. Following creation, the actual yield of free carriers is determined by field-aided escape (i.e., aided by applied bias) of carriers from bimolecular recombination in the high ionization-density regions along the tracks of the incident kilovolt electrons.[5] Snowden et al[9] measured collected charge in SiO_2 capacitors at room temperature using high-energy ionizing radiation (30-MeV LINAC electrons). Their results are again consistent with W_o = 18 eV/pair. In contrast to kiloelectron volt electron irradiation, which produces high ionization-density regions along the relatively short tracks of the incident particles, the very high energy LINAC electron beam produces widely dispersed point ionization in the SiO_2 similar to that which would be produced by energetic photon irradiation.

In this experiment, hole yield in the SiO_2 induced by 13-MeV LINAC radiation pulses was measured at low temperature by the fast C-V measurement technique. Bias voltages were applied to produce fields from -0.6×10^6 to 4.7×10^6 V/cm. To insure that the radiation-generated oxide charge did not significantly perturb the externally applied oxide field, the dose per radiation pulse was maintained below 3×10^3 rads(SiO_2).

The early (~1 ms after pulse) flatband voltage shift ΔV_{FB} is plotted in figure 1 as a function of oxide internal field for the DNA No. 1 n-type samples. (Similar results were obtained for NRTC 1538A MOS capacitors.) To correct for pulse-to-pulse dose variations, the ΔV_{FB} values have been normalized by the calorimeter readings to a nominal dose of 2×10^3 rads(SiO_2). The flatband shift saturates beyond 10^6 V/cm and is essentially symmetrical about the zero V/cm axis.

For a uniform radiation-produced oxide charge density, ρ, consisting of the holes only,

$$\Delta V_{FB} = -\frac{\rho L^2}{2\varepsilon} \qquad (1)$$

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[5] *G. A. Ausman, Jr., and F. B. McLean, Appl. Phys. Lett. 26, 173 (1975).*

[9] *R. E. Leadon, D. P. Snowden, and J. M. Wilkenfeld, Radiation Effects in Semiconductor and Insulator Materials, IRT Corporation, Harry Diamond Laboratories CR-76-152-1 (April 1976).*

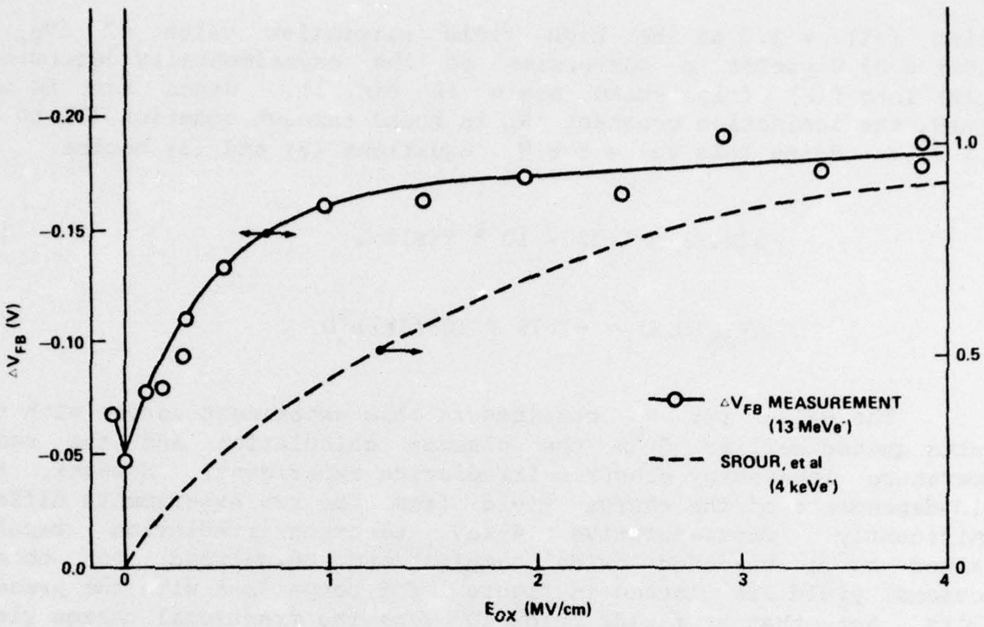

Figure 1. Flatband-voltage shift and corresponding hole yield in MOS capacitors irradiated at 80 K.

where L is the oxide thickness in centimeters and ε is the dielectric constant in F/cm. The charge density may in turn be expressed as a function of oxide dose D, in rads(SiO_2), using appropriate material parameters and the electric-field-dependent fraction f(E) of the radiation-generated holes which escape initial recombination,

$$\rho(D,E) = 2.2 \times 10^{-5} W_o^{-1} f(E)D \quad . \tag{2}$$

Then

$$\Delta V_{FB}(D,E) = (-3.23 \times 10^7) f(E) W_o^{-1} L^2 D \quad . \tag{3}$$

The fractional hole yield as a function of field, f(E), may be obtained from the ΔV_{FB} data in figure 1 by assuming that the asymptotic or saturation value of the flatband shift above ~3 × 10^6 V/cm corresponds to all the holes escaping initial recombination; i.e., f(E) = 1.0.

Setting $f(E) = 1.0$ at the high field saturation value of $\Delta V_{FB} = -0.18 \pm 0.03$ V yields a conversion of the experimentally determined $\Delta V_{FB}(E)$ into $f(E)$ (right-hand scale in fig. 1). Since $f(E)$ is now defined, the ionization constant W_o is found through equation (3) to be (18 ± 3)eV. Using this value for W_o, equations (2) and (3) become

$$\rho(D,E) = 1.22 \times 10^{-6} f(E)D \ , \tag{4}$$

$$\Delta V_{FB}(D,E) = -1.79 \times 10^{6} f(E) L^2 D \ . \tag{5}$$

The value for W_o obtained in this experiment agrees with the results quoted earlier from the plasmon calculation and the room-temperature low-energy electron-irradiation experiment. However, the field dependence of the charge yield from the two experiments differs significantly. Representative 4-keV electron-irradiation results obtained on a hardened oxide sample[10] and normalized to obtain fractional yield are plotted in figure 1 for comparison with the present results. Note that at fields below 10^6 V/cm the fractional charge yield produced by the high-energy radiation is much greater than that produced by the low-energy electrons. The present results are adequately explained by a geminate recombination process in which field-dependent rapid recombination takes place between the members of the widely dispersed electron-hole pairs produced by the high energy radiation.*

3.2 Initial Hole Displacement

To this point, it has been assumed that all the holes remain in the oxide after irradiation. However, evidence has been found in this work that a fraction of the holes escapes the oxide immediately following generation, even at ~80 K. As indicated in a previous paper,[1] the flatband shifts obtained in identical MOS samples at identical doses under negative and positive biases are almost, but not quite, the same. Results obtained on a number of samples from a pair of such measurements are recorded in table II. In each case, the negative bias shift is 10 to 20 percent less than the positive shift. Initially,

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**G. A. Ausman, Jr., private communication.*

[1]*H. E. Boesch, Jr., F. B. McLean, J. M. McGarrity, and G. A. Ausman, Jr., IEEE Trans. Nucl. Sci. NS-22, 2163 (1975).*

[10]*J. R. Srour, O. L. Curtis, Jr., and K. Y. Chiu, IEEE Trans. Nucl. Sci. NS-21, No. 6, 73 (1974).*

TABLE II. INITIAL HOLE DISPLACEMENT IN MOS SAMPLES AT ~80 K

Sample	ΔV_{FB+} (V)	ΔV_{FB-} (V)	E (MV/cm)	Distance (nm)
DNA No. 1	-3.5	-2.7	1.38	9.4 ± 1.4
DNA No. 2	-3.3	-2.5	1.53	9.0 ± 1.3
HAC dry n	-2.7	---	1.14	10.9 ± 2.1
HAC dry p	---	-2.1		
NRTC 850	-6.2	-5.0	1.18	9.1 ± 0.8
NRTC 1538	-2.7	-2.3	0.98	12.3 ± 3.3

it was assumed that this variation resulted from a decrease in the oxide field under negative bias because of a potential drop across the depletion region in the n-type silicon under inversion or deep-depletion conditions. However, this potential drop virtually disappears during a radiation pulse since the depletion region collapses very quickly as carriers are generated in the silicon and transported through the depletion region.[9] Also, the ΔV_{FB} relative decrease at negative biases was exhibited by a pair of samples--HAC dry n and HAC dry p--with identical oxide layers which were irradiated at positive and negative biases respectively, i.e., under accumulation conditions.

The bias effect is adequately explained by postulating that the holes are first transported through extended states in the valence band imediately after the holes are thermalized and before they are captured at a defect site and hopping transport begins. If at a given field the holes are transported an average distance d in the valence band in an oxide of thickness L, then under positive bias and uniform field conditions in the oxide, the hole distribution will be uniformly displaced toward the Si. This displacement leaves the zone between x = 0 (where x is a distance from the metal electrode) and x = d depleted of holes. Similarly, under negative bias a zone between x = L - d and x = L (the Si interface) will be depleted. The corresponding ΔV_{FB} values are

$$\Delta V_{FB+} = -\rho/\varepsilon \int_d^L x dx = -\rho/2\varepsilon \, (L^2 - d^2) \; , \qquad (6)$$

[9] *R. E. Leadon, D. P. Snowden, and J. M. Wilkenfeld, Radiation Effects in Semiconductor and Insulator Materials, IRT Corporation, Harry Diamond Laboratories CR-76-152-1 (April 1976).*

$$\Delta V_{FB-} = -\rho/\varepsilon \int_0^{L-d} x dx = -\rho/2\varepsilon \ (L - d)^2. \tag{7}$$

Then

$$f_d = \left| \frac{\Delta V_{FB+} - \Delta V_{FB-}}{\Delta V_{FB+}} \right| = \frac{2d \ (L - d)}{L^2 - d^2} . \tag{8}$$

Solving for d,

$$d = \frac{Lf_d}{2 - f_d} \tag{9}$$

Values for the initial hole displacement d obtained for several of the MOS samples are presented in table II together with error limits calculated from the estimated probable error in the ΔV_{FB} values. The agreement within the error limits implies strongly that the charge-displacement analysis is essentially correct and that $d \sim 9.5$ nm is appropriate for all the materials examined. If d is assumed to be a schubweg, i.e., $d = \mu_H \tau_H E$ where μ_H is the intrinsic hole mobility, τ_H is the hole dwell time in the valence band, and E is the electric field, then the product $\mu_H \tau_H \approx 7 \times 10^{-3}$ V/cm under these conditions. Unfortunately, the measurements were not performed over a sufficient range of electric field to determine whether d is a schubweg or perhaps a field-independent mean free path.

The error, η, introduced by charge displacement in the measurement of total hole yield under positive bias, is easily found from an extension of the analysis above to be

$$\begin{aligned} \eta &= (\rho L^2/\varepsilon - \Delta V_{FB+})/(\rho L^2/\varepsilon) \\ &= d^2/L^2 \quad . \end{aligned} \tag{10}$$

For a 72.7-nm oxide and $d = 9.5$ nm, $\eta = 0.017$. Therefore, initial charge displacement had a negligible effect on the charge-yield results (fig. 1).

4. DOSE DEPENDENCE OF CHARGE BUILDUP

4.1 Measurements and Results

The response of MOS capacitors to pulsed irradiation at 80 K was measured as a function of dose, applied bias, and time after irradiation.

In the first experiment, a variety of MOS samples (table I) were irradiated at various biases to doses in the 10^3 to 10^6 rad(SiO_2) range and ΔV_{FB} was recorded at 1 ms after the radiation pulse.

Figure 2 shows the flatband shifts as a function of dose, with ΔV_{FB+} normalized by the fractional charge yield, f(E), from figure 1, and the geometric oxide-thickness dependence. The data points indicate a linear variation of normalized ΔV_{FB} with dose up to $\sim 10^5$ rads(SiO_2).

In the second experiment, HAC MOS samples were subjected to high-dose multiple-pulse irradiation (up to 5 pulses at a rate of 60/s; typically 1.75×10^5 rads(SiO) per pulse). HAC n-type samples were biased at 5, 10, and 20 V during irradiation, while HAC p-type samples were biased at the corresponding negative biases. Flatband shifts were measured at 1 and 12 ms after each radiation pulse. The results are plotted in figure 3. The dashed lines represent the predicted flatband shift based on equation (5) for f(E) = 1.0. Above 10^5 rads(SiO_2) the flatband shift evidently ceases to increase linearly with dose. Under negative bias in particular, ΔV_{FB} saturates strongly at a value near the magnitude of the applied bias voltage. Under positive bias, ΔV_{FB} continues to increase with dose, but at a sublinear rate. These experimental results are in qualitative agreement with the observations of Nielsen and Nichols,[11] who measured charge buildup at 90 K under cobalt-60 irradiation.

In the third experiment, the flatband shift in HAC n-type MOS capacitors was observed as a function of time up to 800 s after multiple-pulse irradiations to total doses from 40 to 875 krads(SiO_2) and at bias voltages from 5 to 20 V. Typical results are plotted in figure 4. The observed early (4 ms) flatband shifts conform well to predictions of the initial shift based on equation (5). Also, the shift observed following a single 40-krad (SiO_2) pulse (curve E) shows little change with time. At higher doses--150 krads(SiO_2) and above--significant decay of the flatband shift occurs, particularly at the higher bias voltages.

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[11] *R. L. Nielsen and D. K. Nichols, IEEE Trans. Nucl. Sci.* *<u>NS-20</u>, No. 6, 319 (1973).*

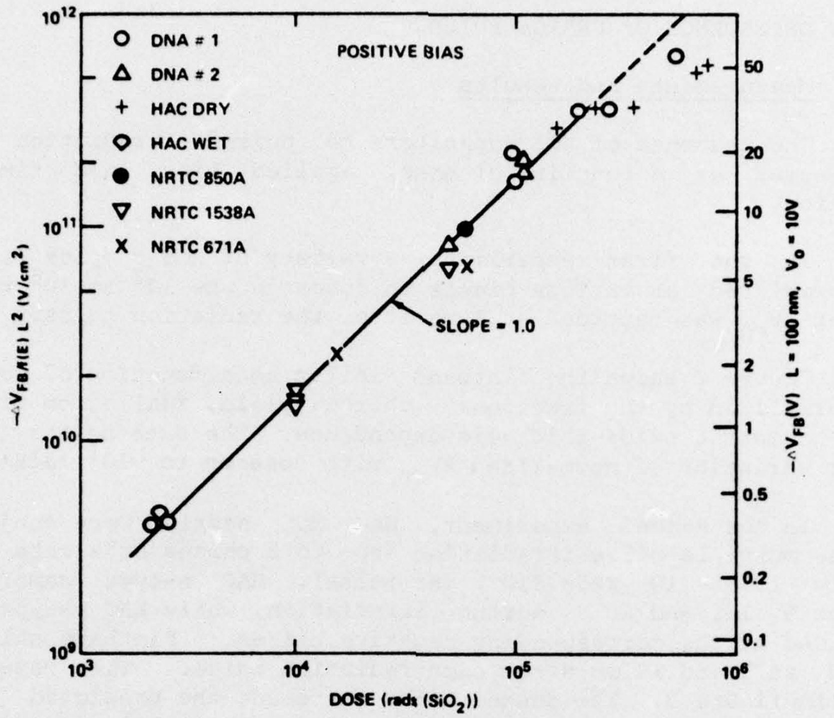

Figure 2. Normalized flatband-voltage shift (*left scale*) and equivalent flatband shift for E = 1 MV/cm and L = 100 nm for various MOS capacitors at 80 K.

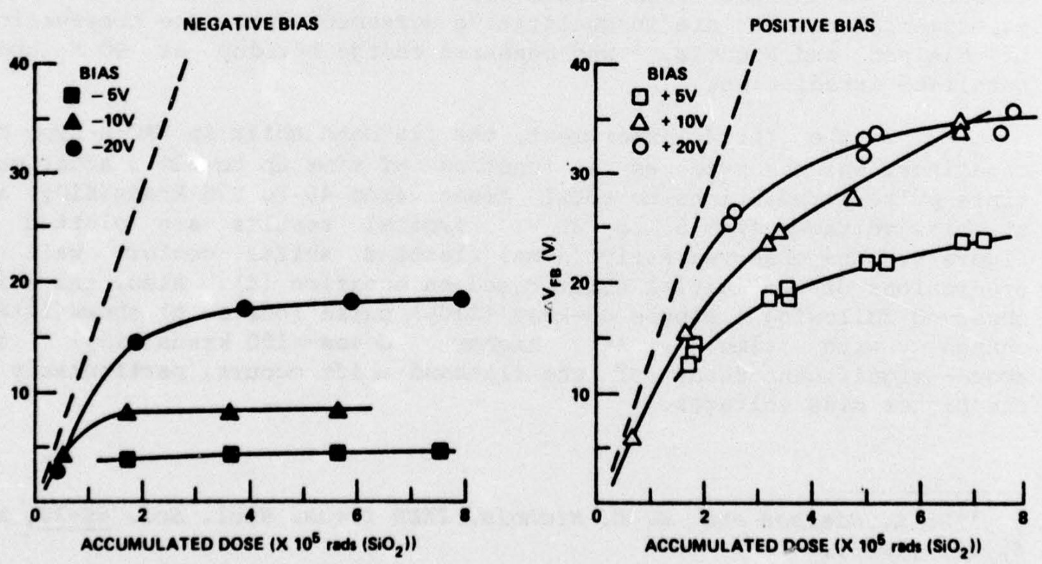

Figure 3. Flatband-voltage shift, ΔV_{FB}, 1 ms after irradiation of HAC p-type (left) and n-type (right) MOS capacitors at 80 K.

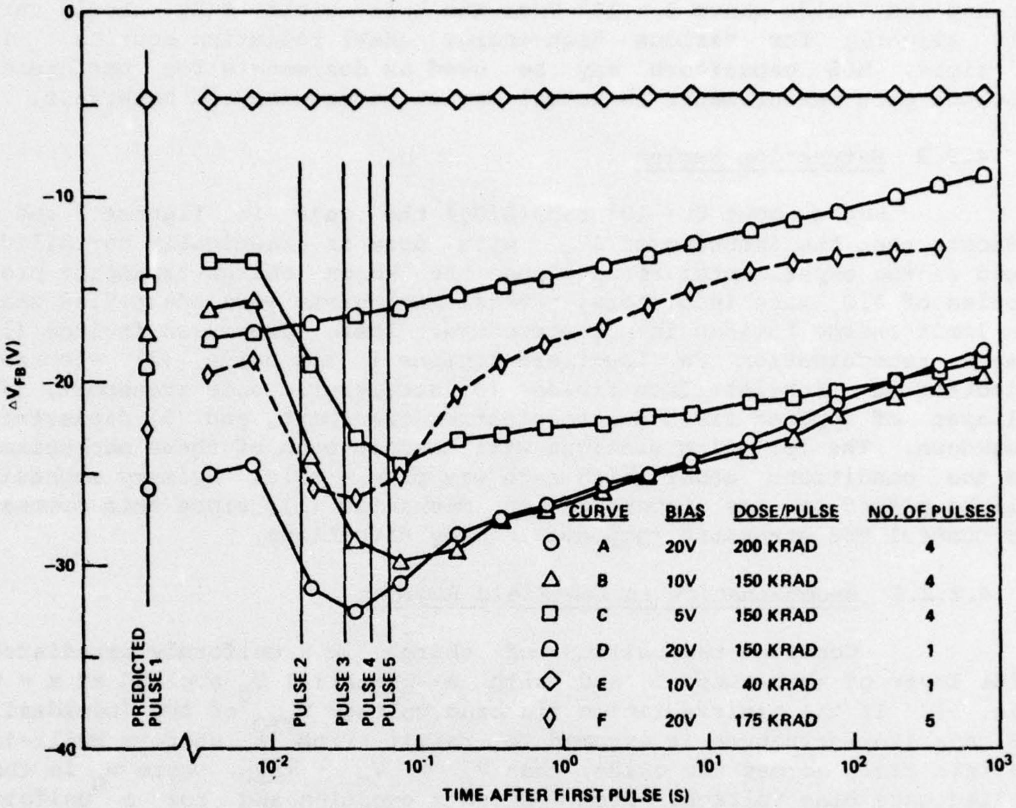

Figure 4. Flatband-voltage shift, ΔV_{FB}, as function of time after first LINAC pulse delivered to HAC dry-n MOS capacitors. Samples received multiple pulses at 60 pulses/s (see legend).

4.2 Discussion

4.2.1 Linear Region

The ΔV_{FB} dose-dependence results presented in figure 2 indicate that, below $\sim 10^5$ rads(SiO_2), the charge buildup in a variety of SiO_2 samples is properly predicted by equation (5). The 80-K shifts are again shown to be large ($\sim$-10 V at 10^5 rads(SiO_2) for 100-nm oxide) and independent of sample source and processing details. This uniform ΔV_{FB} response to pulsed radiation at low temperatures obtained with an early C-V measurement suggests that such capacitors be used as absolute dosimeters. Simply inverting equation (5) yields

$$D = 5.57 \times 10^{-7} \, \Delta V_{FB+}/f(E)L^2 \quad . \qquad (11)$$

For applied fields above 2×10^6 V/cm the hole yield $f(E)$ should vary only slightly for various high-energy (MeV) radiation sources. In principle, MOS capacitors may be used as dosimeters for performing absolute dose measurements in actual device geometries and materials.

4.2.2 Saturation Region

Above about 2×10^5 rads(SiO_2) the data in figures 2 and 3 indicate that the increase of ΔV_{FB} with dose is drastically curtailed. Based on the experimental results and the known charge-transport properties of SiO_2 gate insulators, several mechanisms were identified that can limit charge buildup in MOS structure. These processes include (1) charge recombination in low-field regions in the oxide, (2) electron injection at high-interface fields, (3) accelerated hole transport, (4) collapse of applied field due to electron transport, and (5) dielectric breakdown. The following sections will discuss each of these mechanisms and the conditions under which each may play a role. Primary emphasis will be placed on the recombination mechanism (1), since this process may control MOS structure response in many situations.

4.2.2.1 Recombination in Low-Field Regions

Consider the buildup of charge in a uniformly irradiated oxide layer of thickness L and with a potential V_0 applied at $x = 0$ (fig. 5). If the preirradiation flatband voltage V_{FBO} of the (nonideal) MOS capacitor structure is assumed to result from a uniform built-in electric field across the oxide, then $V_0 = V_G - V_{FBO}$, where V_G is the applied gate bias voltage. From Poisson's equation and for a uniform charge buildup, the electric field in the oxide is given by

$$E(x) = \rho/\varepsilon\ (x - L/2) + V_0/L \quad . \tag{12}$$

For $\rho < |2\varepsilon V/L^2|$, corresponding to $|\Delta V_{FB}| < |V_0|$, the electric field in the oxide is monotonic and the radiation-generated electrons are quickly swept out without interacting with the stationary holes (fig. 5a). Note, however, that the electric field is increasing at $x = L$ and decreasing at $x = 0$ because of the contribution of the hole space-charge field. At a critical dose D_{sat}, ρ approaches $|2\varepsilon V_0/L^2|$ (corresponding to the magnitude of the flatband shift approaching the magnitude of the applied potential), and the electric field at $x = 0$ reaches zero and tries to go negative (fig. 5b). In this case, the electrons being swept toward $x = 0$ come to a virtual halt in the zero field region and undergo efficient recombination with the holes in the vicinity. The result is that the hole density near $x = 0$ is rapidly wiped out. As irradiation of the oxide continues (fig. 5c), the zero point for the electric field and, consequently, the zone of rapid recombination move deeper into the

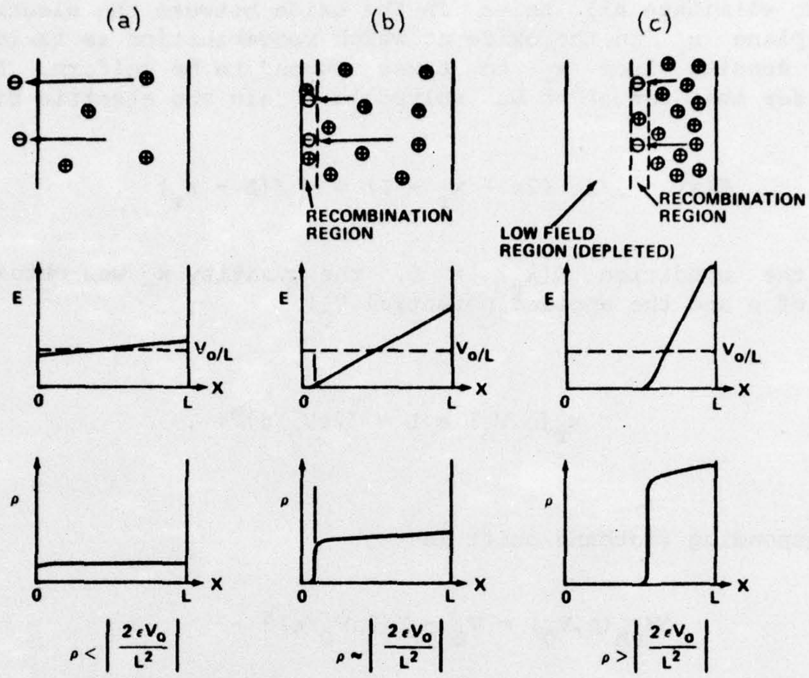

Figure 5. Model for limitation of charge buildup in an oxide layer: (a) electron sweepout; (b) recombination at the interface; (c) recombination in oxide interior.

oxide, "eating away" at the hole distribution. The oxide charge and the total electric field continue to increase at x = L. For irradiation under positive bias, x = 0 in figure 5 corresponds to the electrode interface and x = L is the Si interface. In this case, the recombination process reduces the hole density in a region well removed from the Si interface; consequently, ΔV_{FB+} continues to increase as a function of dose following the onset of recombination, but begins to saturate. For irradiation under negative bias, x = 0 in figure 5 corresponds to the Si interface, and the onset of recombination drastically affects any further increase in ΔV_{FB-} with added dose. In fact, since the net electric field at the Si interface is pinned at zero for $\rho \geq |2\epsilon V_0/L^2|$, the flatband shift under negative bias is similarly pinned to $\Delta V_{FB-} = V_0$. The derivation of the expected dependence on dose of the flatband shift, ΔV_{FB+} under positive bias, was based on this simple model for limiting by recombination and also on certain assumptions. At a given dose above D_{sat} the recombination process is assumed to eliminate all holes in the oxide between the electrode ($x = 0$) and a plane x_r in the oxide at which recombination is taking place. The hole density from x_r to L was assumed to be uniform. Poisson's equation for this situation was solved to obtain the electric field:

$$E(x) = \rho/2\varepsilon \; (2x - x_r - L) + V_0/(L - x_r) \quad . \tag{13}$$

Imposing the condition $E(x_r) = 0$, the quantity x_r was obtained as a function of ρ and the applied potential V_0:

$$x_r(\rho, V_0) = L - (2\varepsilon V_0/\rho)^{\frac{1}{2}} \quad . \tag{14}$$

The corresponding flatband shift is

$$\Delta V_{FB}(\rho, V_0) = V_0 - L(2\rho V_0/\varepsilon)^{\frac{1}{2}}$$

$$\text{for } |\Delta V_{FB+}| > |V_0| \quad . \tag{15}$$

Using equation (4), we may express ΔV_{FB} as a function of oxide dose:

$$\Delta V_{FB+}(D, V_0) = V_0 - 2.68 \times 10^3 \, L\left[V_0 f(E) D\right]^{\frac{1}{2}}$$

$$\text{for } |\Delta V_{FB+}| > |V_0| \quad . \tag{16}$$

This relationship predicts, therefore, that the flatband shift will increase with the square root of the dose for total flatband shifts greater than the applied potential.

The simple recombination model did not include such factors as the field dependence of charge yield in the oxide and the initial displacement of the holes. To aid in a more careful analysis of the ΔV_{FB} limitation mechanisms, a computer program was written to simulate the charge-buildup process in a basic MOS structure. This program repetitively solved Poisson's equation in the x dimension as electron-hole pairs were generated in the oxide to obtain the charge and electric field distribution across the oxide layer as a function of time and dose. The generation rate for electron-hole pairs in each x subinterval was governed by the instantaneous electric field in that interval through the experimental yield/field relationship in figure 1. The program allowed for initial displacement of the holes according to the schubweg model, following which the holes were assumed to be immobile. In keeping with the discussion above, the electrons were assumed to be infinitely mobile; that is, they move without limit unless stopped at a point of field reversal. Hole-electron recombination was allowed only at field reversal points.

Representative results from this computer model are shown in figure 6. No parameters were adjusted to obtain these results; all the constants used in the calculation were derived from material properties and the data in figure 1 and table II. Field and hole density profiles in the oxide are shown for doses to 10^6 rads(SiO_2) for an 87.5-nm oxide under 10-V bias (HAC dry n or p). Note the apparent concentration of the hole buildup and, consequently, the electric field near the x = L interface (Si interface under positive bias) as the dose increases. Other workers have also found evidence for concentration of the holes near the Si interface under positive bias at low temperature.[11,12] It is important to recognize that bunching of the holes near the interface at low temperature does not require hole transport or preferential trapping in that region, but results from the progressive elimination of holes in the balance of the oxide.

Both the simple model and computer model predictions for the flatband shifts in the HAC samples as a function of dose under negative and positive bias are compared in figure 7. Also plotted are the experimental ΔV_{FB} data from figure 3 (points). Both the simple recombination model and the computer simulation results reproduce the sharp limitation of ΔV_{FB} to essentially the applied negative bias. The computer calculation shows a stronger limitation of the positive bias shift than predicted by the simple analytic model; this is primarily a result of hole loss by initial transport which becomes significant as the electric field near the Si interface increases and the hole region shrinks. The 5- and 10-V computer-model curves agree with the

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[11]*R. L. Nielsen and D. K. Nichols, IEEE Trans. Nucl. Sci.* <u>*NS-20*</u>*, No. 6, 319 (1973).*

[12]*E. Harari, S. Wang, and B. S. H. Royce, J. Appl. Phys.* <u>*46*</u>*, 1310 (1975).*

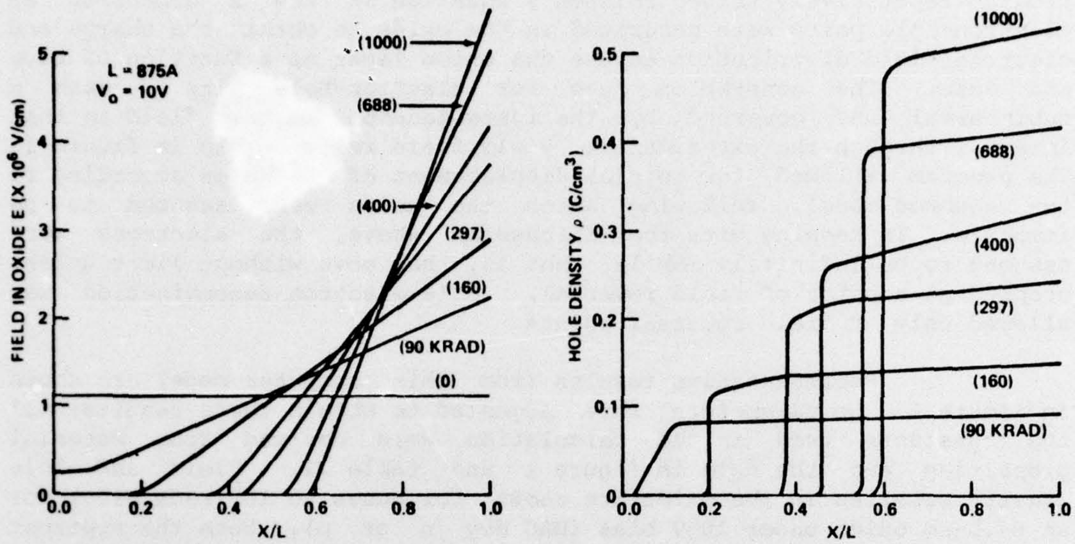

Figure 6. Calculated field and hole density profiles in the oxide as a function of dose at 80 K.

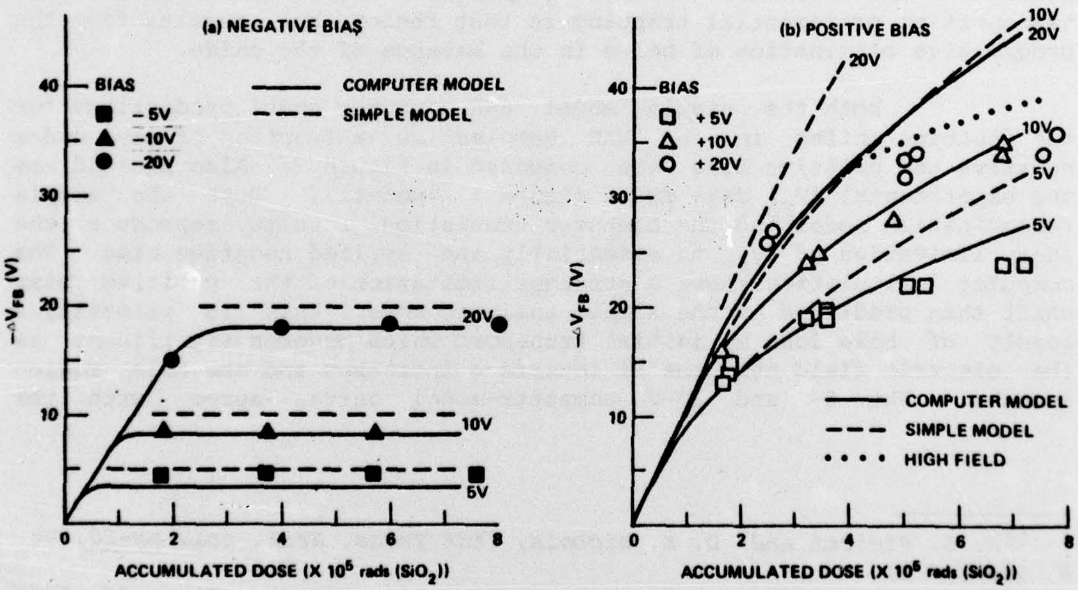

Figure 7. Comparison of model calculations and experimental results on the flatband-voltage shift under (a) positive and (b) negative bias at 80 K.

experimental results, indicating that the recombination mechanism accounts for most of the charge-buildup limitation in these cases. The 20-V bias data points show strong ΔV_{FB} saturation above 5×10^5 rads(SiO_2) which is not predicted by the computer model; evidently other processes, which will be discussed further, contribute to buildup limitation in this case.

4.2.2.2 Electron Injection at High Fields

The computer simulation of the 20-V buildup predicted that the total electric field at the Si interface should have increased beyond 5×10^6 V/cm for doses above 3×10^5 rads(SiO_2), while the field in the 10-V case was predicted to remain below that value to above 8×10^5 rads(SiO_2). Mitchell[13] noted that high interface fields would be expected to cause injection of electrons into the oxide from the silicon which would in time result in elimination of some holes in the oxide by recombination. Powell[14] measured significant electron injection via tunneling for interface fields greater than 6×10^6 V/cm. Since the tunneling current increased exponentially with the field, this process could result in a strong saturation of the flatband shift above a critical value. A crude attempt at including the electron injection process in the computer model yielded results (dotted line, fig. 7b) in reasonable agreement with the experimental data.

If it is assumed that a mechanism such as tunneling limits the interface field to $E(L) = E_{max}$, then the maximum flatband shift which can be obtained is

$$\Delta V_{FB+} = V_0 - LE_{max} \quad . \tag{17}$$

The dose at which this flatband shift is first attained may be estimated from the analytic recombination model introduced earlier. Substituting equation (14) into equation (13), setting $E(L) = E_{max}$ and rearranging,

$$\rho(E_{max}, V_0) = \varepsilon E^2_{max}/2V_0 \quad , \tag{18}$$

or, applying equation (4),

$$D_{sat} = 1.39 \times 10^{-7} \, E^2_{max}/f(E)V_0 \quad . \tag{19}$$

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[13] *J. P. Mitchell, IEEE Trans. Elec. Dev. ED-14, No. 11, 764 (1967).*
[14] *R. J. Powell, IEEE Trans. Nucl. Sci. NS-22, 2240 (1975).*

For an 87.5-nm oxide biased at 20 V and $E_{max} = 6.5 \times 10^6$ V/cm, the saturation shift of -37 V should be attained at 3.7×10^5 rads(SiO_2). For 5-V bias under similar conditions, ΔV_{FB+} = -52 V at D_{sat} = 1.9×10^6 rads(SiO_2). Thus, field limiting is much more likely to occur at higher applied voltage.

4.2.2.3 Hole Transport

As noted previously, figure 4 shows that significant decay of ΔV_{FB} occurs at 80 K for pulsed irradiation of SiO_2 samples to doses above 150 krads(SiO_2). As plotted, ΔV_{FB} for most of the samples decreases linearly as a function of log t (time). This logarithmic flatband shift decay is typical of hole loss by transport through the oxide.[1] Although the discussion thus far has assumed that the holes (after an initial displacement) are essentially immobile near 80 K, hole motion is greatly accelerated at higher fields.[4] The curves in figure 4 show evidence that the rate of ΔV_{FB} decay is bias dependent: the shift with 10-V applied, shown in curve B (four pulses of 150 krads each) decays more rapidly than the corresponding 5-V shift (curve C); the 20-V shift for one 150-krad pulse (curve D) although initially smaller, decays even more rapidly. If the decay were due to electron injection, the samples biased at 20 V which received multiple pulses should show much more rapid charge loss since the space-charge contribution to the interface field is greater; however, this was not observed (except in the sample that received five 175-krad pulses (curve F), which will be discussed). The charge-loss mechanism here is therefore believed to be field-activated hole transport at the moderately high (2.3×10^6 V/cm) field present across the oxide.

The sample exposed to five 175-krad pulses at 20-V bias (fig. 4, curve F) shows relatively rapid charge loss which slows down in about a minute. This sample was exposed to the radiation pulses while mounted in an evacuated sample holder maintained at 80 K. The only mechanisms for removing heat from the sample were radiation to the 80-K surroundings (negligible at low temperature) and direct thermal conduction along the two header lead wires to the socket. It is therefore likely that this sample underwent essentially lossless heating when subjected to 875 krads(SiO_2) in 67 ms. The temperature rise was estimated to be ~60 K from the low-temperature heat capacity of the

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[1] *H. E. Boesch, Jr., F. B. McLean, J. M. McGarrity, and G. A. Ausman, Jr., IEEE Trans. Nucl. Sci. NS-22, 2163 (1975).*

[4] *F. B. McLean, H. E. Boesch, Jr., and J. M. McGarrity, Hole Transport and Recovery Characteristics of MOS Gate Insulators, IEEE Nuclear and Space Radiation Effects Conference, July 1976.*

silicon substrate and the header material. At ~140 K, hole transport is greatly accelerated compared to its rate at 80 K. While this mechanism does not strictly apply to devices operated at 80 K, the possibility that devices may undergo significant transient heating in a real radiation environment should not be ignored.

4.2.2.4 Collapse of Applied Field

Another mechanism that may limit oxide-charge buildup in devices operated in pulsed nuclear environments is collapse of the bias voltage applied across the oxide during a radiation pulse. Since the radiation-generated electrons are mobile, their motion through the oxide under the applied field constitutes a current which may discharge the gate-substrate capacitance, C. If the circuit that consists of the internal resistances of the device and any series external elements has an equivalent series resistance R such that RC is greater than the duration of the radiation pulse τ, the bias on the device will collapse during a radiation pulse of sufficient magnitude. For $RC > \tau$, the fractional charge loss on C due to electron movement only is given by

$$\Delta Q/Q = 1/2\rho AL/CV_G = \rho L^2/2\varepsilon V_G \tag{20}$$

where A is the oxide area and Q is the charge on the capacitor. The dose D_{sat} at which complete field collapse (discharge, corresponding to $\Delta Q/Q \sim 1$) should first occur, may be obtained through application of equation (4):

$$D_{sat} \sim 6 \times 10^{-7}\, V_G/f(E)L^2 \ . \tag{21}$$

The corresponding saturation flatband shift is equal to the magnitude of the applied voltage:

$$|\Delta V_{FB}(D_{sat})| \sim |-V_G| \ . \tag{22}$$

4.2.2.5 Dielectric Breakdown

Another mechanism may operate if the ones discussed so far fail to limit charge buildup in an MOS structure or if weaknesses exist in that structure. During the course of the experiments, a few MOS capacitors short-circuited under test, usually after receiving a high dose (greater than 3×10^5 rads(SiO_2)) and following irradiation at $V_G \geq 20$ V. Yang, Johnson, and Lampert[15] have investigated a self-enhanced breakdown mechanism in which electrons tunneling into the SiO_2 in high-field regions become "hot" and generate holes by impact ionization, thereby enhancing the local field and therefore the tunneling current. A sudden increase in interface field due to holes generated in the oxide by a radiation pulse may trigger this failure mechanism in an MOS structure with oxide defects (near-pinholes) which cause local field concentration. In complex devices such as LSI logic and CCD's, the device geometry (e.g., metallization pattern) may cause field concentration in small areas, leading to device burnout.

4.2.2.6 Applicability to Higher Temperatures

It should be noted that most of the flatband-shift limitation processes which have been discussed are not inherently restricted to situations in which the device is irradiated at low temperature. With the exception of the hole-transport processes, the modeling and conclusions presented are valid for any situation in which little hole motion takes place during the radiation pulse. The data of Hughes et al[3] and Srour et al[10] indicate that little hole motion occurs in less than 10^{-8} s even at room temperature. Therefore, most of the processes discussed should limit the initial shift for room temperature irradiations in most pulsed nuclear and flash x-ray environments. At room temperature, rapid charge removal by hole transport ("short-term annealing") takes place within seconds after irradiation.[1] The flatband or threshold shift remaining after transport is presumably determined by the highly processing-dependent density of deep-hole traps in the oxide which capture some of the transported holes. Consequently, any process which limits the initial shift should cause a proportionate reduction in the shift remaining at late time.

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[1] *H. E. Boesch, Jr., F. B. McLean, J. M. McGarrity, and G. A. Ausman, Jr., IEEE Trans. Nucl. Sci. NS-22, 2163 (1975).*

[3] *R. C. Hughes, E. P. Eer Nisse, and H. J. Stein, IEEE Trans. Nucl. Sci. NS-22, 2227 (1975).*

[10] *J. R. Srour, O. L. Curtis, Jr., and K. Y. Chiu, IEEE Trans. Nucl. Sci. NS-21, No. 6, 73 (1974).*

[15] *W. C. Johnson, IEEE Trans. Nucl. Sci. NS-22, 2144 (1975).*

5. CONCLUSIONS

The yield of holes produced in SiO_2 subjected to high-energy short-pulse radiation at ~80 K was measured as a function of electric field, and a hole-electron pair-creation energy of 18 eV was derived. Early differences in ΔV_{FB} under positive and negative biases at 80 K imply an initial hole displacement of ~9 nm at 10^6 V/cm. The extremely large flatband-voltage shifts attained in MOS structures per unit dose at 80 K were shown to be predictable, processing independent, and linear in dose to ~10^5 rads(SiO_2). At higher doses the shifts increase sublinearly with dose, primarily as a result of recombination in a low-field region of the oxide. Other mechanisms such as electron injection and hole transport probably play a role as radiation-induced space-charge fields in the oxide become large. The limitation processes should be effective even at room temperature so long as little hole transport takes place during irradiation.

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